Creating an Illusion of Movement between the Hands Using Mid-Air Touch

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***Abstract*—Apparent tactile motion (ATM) has been shown to occur on many contiguous parts of the body, such as the fingers, forearms, and back. More recently, the illusion has also been elicited on non-contiguous parts of the body, such as between one hand and the other, either when the hands are interconnected or not interconnected by an object (e.g., when holding a tablet or not). Here we explore the reproducibility of the intermanual tactile illusion of movement between two free hands by employing mid-air tactile stimulation. We investigate the optimal parameters to generate a continuous and smooth motion using two arrays of ultrasound speakers and two stimulation techniques (i.e., static vs. dynamic focal point). In the first experiment, we investigate the occurrence of the illusion when using a static focal point, and we define a perceptive model. In the second experiment, we examine the illusion using a dynamic focal point, defining a second perceptive model. Finally, we discuss the differences between the two techniques.**

***Index Terms*—Mid-air Touch, Tactile Illusions, Touch, Apparent Tactile Motion, Haptics.**

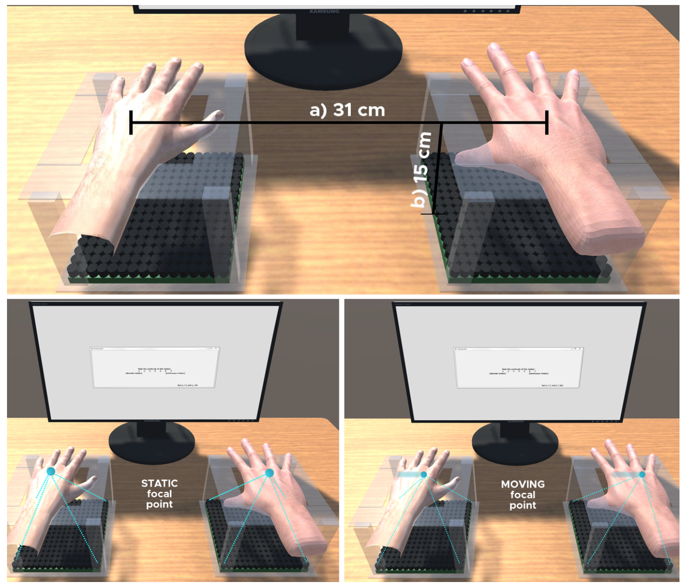

Fig. 1. Experiments setting. TOP: For both experiments, a) the distance between the palm of the two hands was set at 31 cm, and b) the hands were resting on the two acrylic boxes at a distance of 15 cm above the two mid-air haptic devices. LEFT: In experiment 1, a static focal point was delivered to the center of the distal part of each palm. RIGHT: In experiment 2, a dynamic focal point was delivered to the distal part of each palm.

I. Introduction

Tactile feedback is increasingly being implemented in modern technology, and vibrotactile controllers are well known in the classic games industry (e.g.,for the Sony PlayStation, Microsoft Xbox, Nintendo Wii U). Recently, virtual reality (VR) companies have also been trying to implement tactile feedback in their controllers, such as in the Oculus Rift, the HTC Vive, or the Sony VR headsets. These efforts underline the increased demand for using haptic feedback to make the user's experience more immersive. As of today, tactile feedback is mainly provided statically to the hands (i.e., by means of actuators providing a vibration without any motion pattern), hence limiting the potential for experiencing dynamic situations. For instance, we can imagine being a superhero moving an energetic wave from one hand to the other and feel it growing before throwing it at an enemy, or we could feel a shock wave moving under our feet after an explosion in a game. Dynamic movement is also something we experience in real-life situations, for example, the wind blowing across our face or the waves of the sea moving against our body. Hence, to increase immersiveness in a virtual environment (VE), emerging haptic technologies should be able to provide a tactile sensation of movement to render additional and more realistic experiences.

To achieve a sense of motion, we can draw upon research in psychology on tactile illusions of movement such as *apparent tactile motion* (ATM). The advantage of using a perceptual illusion to elicit the feeling of motion is that we can achieve the same perceptual sensation using a drastically reduced number of actuators. This both reduces the number of attachments on the user's body and the programming complexity. Previous research has demonstrated the successful use of ATM: Israr et al. delivering movement on the back [1], [2], Zhao et al. [3] rendering movement between two hands interconnected by a tablet, and Pittera et al. [4] investigating the ATM illusion between two non-interconnected hands. All of these studies have made use of physical touch.

Due to the evolution of haptic technology, we now have alternative ways to deliver tactile feedback, with the latest innovations enabling its delivery in mid-air. The advantage of using such technology is the possibility of creating and delivering tactile feedback without the need for cumbersome attachments on the user's skin. In this study, we chose to employ a commercially available ultrasound-based device that showed potential for creating a new variety of experiences. This device has previously been used to enhance the user experience of short movies [5] and art exhibitions [6]. Carter et al. [7] employed ultrasound arrays as an input interface, allowing color rendering, pinch-to-zoom interaction, and the possibility of interacting with a web application. Long et al. [8] were able to successfully render volumetric shapes.

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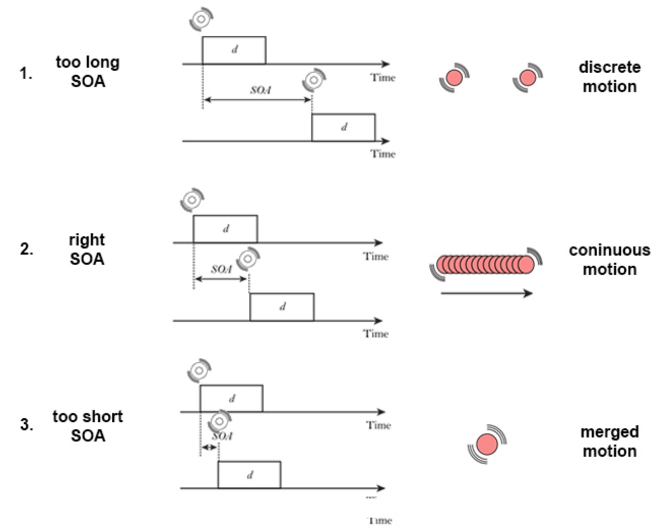

Fig. 2. Representation of apparent tactile motion, showing the perceptive effect accordingly to different stimulus onset asynchronies (SOAs). If the SOA is too long, the perception will result in two discrete vibrations (top). If the SOA is too short, the perception will be merged into a single point (bottom). With an optimal SOA, motion will be perceived (center).

Obrist et al. [9] delivered emotional content to the hand using mid-air tactile stimulation. Finally, there have also been attempts to use mid-air touch to replicate the findings of traditional psychological research that employs physical touch. For instance, Horiuchi et al. [10] replicated the rubber hand illusion using mid-air stimulation and projected images.

With the proliferation of VR and augmented reality (AR) technology, there has been an increased interest in creating more immersive and compelling experiences through integrating tactile stimuli. Being scalable, attachment free, and temporally precise, mid-air technology can expand the set of tools designers use to design more immersive and realistic scenarios in traditional console games and VR and AR environments.

We used ultrasound mid-air technology to investigate the ability to recreate the ATM illusion. Having the ability to easily create different tactile patterns, we investigated the optimal values (in terms of frequency, duration, SOA, and direction) needed to render a smooth tactile sensation of movement through 1) a static and 2) a dynamic focal point (see Fig. 1). We provide and compare two perceptive models, one for each of the above techniques. Finally, we compare our results with a previous study that used physical tactile stimulation (i.e., vibrotactile actuators) [4]. Although we hypothesize that dynamic point stimulation will result in a stronger illusion of movement compared to static point stimulation, it is not clear if the results from the dynamic mid-air focal point will differ from those of physical touch on the hands. Our results suggest that the dynamic mid-air focal point is indeed capable of providing a greater illusion of movement compared to a static point, and it works as well as physical touch. This investigation contributes to the basic understanding of mid-air tactile perception, allowing the representation of more complex scenarios that include tactile movement. With this investigation, we also aim to provide designers of tactile displays with an understanding of the optimal parameters for the design of a smooth tactile movement.

II. Previous research

The sense of touch is a multifaceted system that pervades the whole body and encompasses cutaneous inputs from the mechanoreceptors in the skin, accounting for the sensation of pressure, vibration, pain, temperature, and pleasure associated with a certain tactile stimulation. In its broader meaning, haptics, it encompasses all those sensations associated with an active touch (kinesthetic inputs from the muscles, tendons, and joints), providing updated information on the position of the limbs in space (proprioception) and the extent of muscle stretch, as well as information on an object's 3D shape and texture [11]. Hence, rendering the complexity of this system through modern actuators still represents a challenge. In this paper, we explore the use of tactile illusions as a promising approach to overcome current limitations in creating complex tactile sensations, one which obviates the need to focus on the precise rendering of their components. In other words, tactile illusions can provide design shortcuts for creating convincing tactile experiences. Here, we are particularly interested in those illusions that can render a tactile sensation of movement.

A. *Tactile illusions of movement*

Prior studies of physical touch stimulation identified three main types of illusions of movement using a psychophysical approach [12], [13], [14]: 1) the cutaneous rabbit illusion, 2) the haptic funneling illusion, and 3) ATM (more recent tactile illusions of movements are described in [15], [16], [17]).

In the cutaneous rabbit illusion, two vibrotactile actuators are modulated in a timely fashion to create a third illusory perceptual sensation like that of a rabbit hopping in-between the two real actuators [18]. In the haptic funneling illusion, two actuators vibrate at different intensities, creating a third, intermediate perceptual point whose position is determined by the variation in the intensity of the two vibrations [19]. In this study, we focus on the ATM illusion. Here, two actuators are activated while modulating the SOA so that the user perceives a feeling of movement between the two sites of stimulation (see Fig. 2) [20]. There are three possible scenarios: a) If the SOA is too long, then the two vibrations will be perceived as discrete and no illusion of movement will occur (Fig. 2, top); b) if the SOA is too short, the two vibrations will be perceptually merged into a single one and no illusion of movement will occur (Fig. 2 bottom); c) if the SOA is optimal, the two vibrations will be perceived as a movement (Fig. 2, center). Many other tactile illusions are being studied, but their description is beyond the scope of this paper (for a more extensive overview on tactile illusions, see [12], [21]).

B. *Apparent tactile motion*

The phenomenon of ATM has been studied since the early 1990s [20], [21], [22], [23], [24]. In these pioneering studies, authors have investigated the fundamental parameters that allow for smooth tactile motion. They concluded that there was a significant positive correlation between the duration of the stimulus and the SOA. This same relation was also found in the visual modality version of the apparent tactile illusion (e.g., two static lights turning on and off at a certain frequency, providing an effect of motion) [23]. Research on ATM is ongoing, with different aspects of the phenomenon being studied. Miyazaki et al. explored the illusion on the fingers [25], Lechelt et al. on the forearm [26], and Israr et al. on the back [1], [3]. Zhao et al. investigated the ATM between two hands interconnected by a tablet [3]. Moreover, Pittera et al. [4] recently illustrated how the illusion occurs when the two hands are not interconnected. Finally, Wilson et al. studied ATM occurring on a single hand using mid-air stimulation [27]. These studies have shown the main factors that contribute to a smooth sensation of motion: the stimulus duration and the SOA between the first and second tactile stimulation.

The apparent tactile illusion can be easily applied to the realm of VR tactile applications. In fact, we could provide the user with a smooth feeling of motion, making the virtual experience even more immersive. Currently, one of the main limitations when providing tactile feedback resides in the attachment of more cumbersome devices, which could break the immersiveness in the virtual environment. New emerging technologies such as mid-air haptic devices could tackle this issue. These devices are capable of delivering tactile stimulation without the need for attachments on the skin (see section II-C). Moreover, they allow more control over parameters such as frequency, intensity, direction, ramp up/down of the signal, and signal waveform. However, to date, there is no empirical evidence of their ability to induce ATM or of whether the key variables to obtain smooth motion are the same as when using physical touch (i.e., duration and SOA). We do not know if the duration and SOA of the tactile stimuli would still be the main key variables. In this paper, we investigate if mid-air touch can elicit an illusion of motion and the parameters which need to be controlled in order to achieve a smooth motion sensation. Since this new technology allows the design of different mid-air tactile patterns, and to increase the chance of eliciting a smoother sensation of movement, we replicate ATM employing two different tactile patterns: a static focal point and a dynamic focal point.

C. Mid-air haptic technology

Current mid-air haptic devices deliver tactile feedback through three main modalities: air, laser, and ultrasound. Laser mid-air devices are based on the thermoelastic effect, using indirect laser radiation to convey tactile feedback [28]. One of the drawbacks of this technology is that the user must wear an attachment on the skin both to perceive the tactile feedback and for protection. Airborne technology represents a safe alternative for conveying tactile feedback. Air is pushed through a nozzle and, depending on the specific device employed, can travel for several meters from the source [29]. The main limitation is that air tends to dissipate quickly and, even when it is possible to contain its dissipation (i.e., in the case of vortex technology), its spatial resolution is low, making the achievement of a localized sensation impossible [29], [30], [31].

Fig. 3. Ultrasonic technology allows the display of tactile feedback in mid-air using a series of ultrasonic transducers emitting sound waves that can be felt when they are spatially and temporally aligned, creating a focal point. (Picture provided by UltraHaptics LtD)

One of the most promising mid-air technologies employs focused ultrasound, exploiting the principle of acoustic radiation force [32], [7]. The ultrasonic technology was originally introduced by Hoshi et al. [32] and allows the delivery of tactile feedback in mid-air using a series of ultrasonic transducers. These emit sound waves at ultrasonic frequencies that can be felt when they are spatially and temporally aligned, creating a focal point (Fig. 3). Such a setup allows users to experience tactile feedback without any direct contact or attachment to the body. The psychophysical knowledge of this mid-air haptic technology is still in its infancy, but prior work has mapped high-frequency stimulations (i.e., 250 Hz) to the Pacinian corpuscles (mechanoreceptors in the glabrous skin, sensitive to high-frequency vibrations from 50 Hz to 10 kHz [33]) and low frequency stimulations (i.e., 16 Hz) to the Meissner corpuscles (mechanoreceptors sensitive to low frequency vibrations below 80 Hz [34]) [35]. The ultrasound mid-air technology has a greater temporal and spatial resolution (40 kHz, 1 cm, [8]) compared to vortex based systems and compressed air systems. It is possible to control the position and intensity of the focal points at high frequency (16 kHz), allowing a multitude of tactile patterns by means of different durations, frequencies, and ramp up/down of the signal. In addition, this technology is safe and scalable.

III. Study setup and approach

The objective of this study is to investigate the reproducibility of ATM between two non-interconnected hands using mid-air tactile stimulation. Furthermore, we are interested in learning whether a static or dynamic focal point will provide the smoothest tactile motion sensation.

In the following two sections, we present two studies that explore the optimal parameters needed for creating a smooth tactile transition from one hand to the other. In both experiments, we followed a psychophysical approach to determine the relationship between the mid-air stimuli and the resulting tactile perception (i.e., occurrence of ATM).

We used two mid-air haptic devices developed by Ultrahaptics Ltd. (www.ultrahaptics.com). This device consists of an array of ultrasound speakers (16 x 16) that allows precise control of the tactile stimuli delivery (e.g., frequency, amplitude, SOA, ramp up/down of the signal, waveform, and duration)(see Fig. 1). We programmed a graphical user interface (GUI) in C# to guide participants through the experiment. The ultrasonic haptic boards were controlled through a program written in C++ and connected to the GUI through the TCP/IP protocol. The boards were synchronized using high precision timers (ms order). The tactile focal points employed in the two experiments were designed using amplitude modulation (i.e., to create a 200 Hz focal point, the intensity of the point was alternating from 0% to 100%, 200 times per second). The intensity change followed a sinusoid curve to minimize the noise of the devices. In experiment 1, we projected a single static focal point onto the distal part of each palm. In experiment 2, the focal point moved along the distal part of each palm in a straight line, from the right to left or left to right, at different SOA values. We chose to project the tactile feedback onto the distal part of the palm because, especially for experiment 2, we needed a uniform (flat) area on which to display the focal point. In fact, if the dynamic mid-air point hit the skin at different heights, the perception could be non-uniform and hard to perceive.

Participants were sitting on a chair with their two arms leaning on arm supports and their palms downwards on two boxes (see Fig. 1). The boxes were acrylic structures, each containing a mid-air haptic device with a rectangular hole of 10 x 8 cm in the center to allow the mid-air stimulation to reach the distal part of participants' palms. The distal part of the palm of each hand was aligned with the center of the boxes' hole, where the mid-air stimulation was provided. The location of the stimulus delivery did not vary with the hand size; the hand was always hit at the center of the distal part of the palm. The boxes were designed to keep users' hands at a constant distance of 15 cm above the ultrasound array, which is within the optimal working range of the device. The distance between the palms was kept at 31 cm as in [4]. Instructions were provided on a screen. Ethics approval for this research was obtained by the university's Science and Technology Ethics Committee.

IV. Experiment 1: Tactile Illusion of Movement with a Single Fixed Focal Point

The aim of this experiment was first to investigate whether ATM between the hands occurs when using a mid-air stimulation. If the illusion did occur, the second objective was to determine the optimal parameters to elicit a smooth illusion of movement to define a perceptive model. In this first experiment, we investigated the illusion using a single static focal point projected onto the distal part of participants' palms.

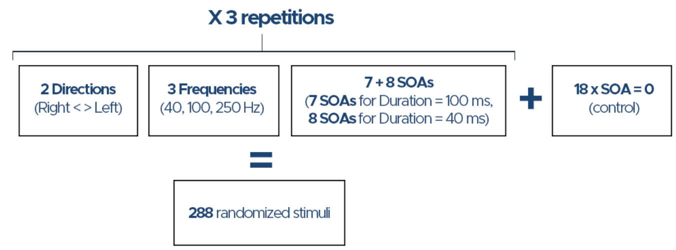

Fig. 4. Experimental design for experiment 1. Every mid-air haptics stimulus was a combination of the four variables (i.e., duration, direction, frequency, SOA), and a control condition with SOA set at 0, for a total of 288 randomized stimuli. The picture is not representative of the order of presentation of the stimuli.

A. Method

We first conducted a pilot experiment with seven participants (three females, age $\mu = 27.4$, SD ± 3.6) to determine the frequency and duration of the mid-air tactile stimulation. Based on previous studies [3], [36], [4], we tested three different frequencies (70 Hz, 100 Hz, and 250 Hz), and two durations (100 ms and 400 ms). While testing the smoothness of the motion in our pilot experiment (using the same study set-up as described above, see Fig. 1), the only pair of frequencies that was statistically similar was the 70 Hz and 100 Hz ($p > .5$). Hence, for the main experiment we selected only the 100 Hz and 250 Hz frequencies. In addition, knowing that mid-air touch perception is associated not only with the Pacinian corpuscles (receptors for high-frequency vibrations from 50 Hz to 10 kHz) but also with the Meissner corpuscles (receptors for low-frequency vibrations < 80 Hz) [35], we additionally tested the 40 Hz frequency, for a total of three frequencies (40 Hz, 100 Hz, and 250 Hz).

Based on the pilot study and accounting for the mechanoreceptors relevant for high and low-frequency vibrations, the experimental design for experiment 1 consisted of three blocks of 96 randomized mid-air tactile stimuli, for a total of 288 stimuli.

We chose two stimulus durations (i.e., 100 and 400 ms). For each duration, we chose a different set of SOAs, equally divided as in [3], [4]. For the 100 ms duration, the SOAs ranged from 15 ms to 190 ms for a total of eight intervals, and for the 400 ms duration, SOAs ranged from 15 ms to 350 ms, for a total of seven intervals. These different SOA ranges are required to reach a plausible effect of movement [3], [4]. For each duration, we also added an SOA = 0 as a control condition to account for random responses from participants. Every tactile stimulus was set to ramp up and down at a time equal to the 20% of the stimulus duration, as in [3], [4]. Therefore, every stimulus was a combination of duration (100 ms and 400 ms), SOA (the two different sets, plus the control SOA), frequency (40 Hz, 100 Hz, and 250 Hz) and direction (from left to right and vice-versa) (see Fig. 4 for an overview).

Before the testing phase began, participants had the opportunity to familiarize themselves with the mid-air tactile stimulation. A minimum of three pairs of stimuli were presented in a series to participants' palms while the researcher ensured that the user understood the experimental procedure. After this training phase, stimuli were presented one at a time, with at least a five-second gap to avoid tactile habituation. After the stimulus occurred, participants were guided by the GUI to report verbally if they felt a sensation of movement between the hands. In the case of a negative answer, the subsequent trial was presented. Instead, if a feeling of motion was reported, the participant was asked to indicate verbally the smoothness of the motion on a rating scale visible on the GUI, ranging from 1 (discrete motion) to 7 (continuous motion). Participant's answers were recorded on the computer by the researcher. Additionally, participants could ask to repeat the stimulation. Each block of 96 stimuli was separated by a two-minute break. Participants wore headphones to mask environmental and device noises. Moreover, a beep sound was played through the headphones before the beginning of each trial. Overall, the experiment lasted 45 minutes. All participants were compensated with a £7.5 voucher for participating in the experiment.

B. Participants

A total of 20 participants took part in the study (nine females, age $\mu = 26.8$, SD $\pm$ 7.7). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained to them.

C. Results

To ensure that the rating scale was used appropriately, we checked the ratings for the SOA = 0 (control trials). The overall ratings were respectively 0.39 and 0.12 for durations of 100 ms and 400 ms, meaning that participants did not feel movement when the tactile point was provided at the same time on the two hands. Users' ratings (1, discrete motion to 7, continuous motion) were averaged for the two durations across participants.

Fig. 5 illustrates the average ratings as a function of SOA for the two durations, the two directions, and the three frequencies, along with best-fit quadratic trends. The two lowest parts of the curves correspond to low SOAs (left part of the curves = merged tactile perception) and to high SOAs (right part of the curves = discrete tactile perception). The peaks of the curves are reported in Table I, and they correspond to the optimal values of the SOAs needed to achieve a smooth sense of motion. On average, the optimal SOA value was found to be 177.21 ms.

Fig.5 suggests non-linear trends of the rating scores. Moreover, comparing our results with previous research ([3], [32]), we can hypothesize that with very small and very large values of SOA, participants' ratings of the smoothness of motion will decrease. Therefore, a quadratic model seems more appropriate for describing our dataset. Using R software (v. 3.5.1) with the *nlme* package, we fit our data to a quadratic model accounting for individual differences between the subjects.

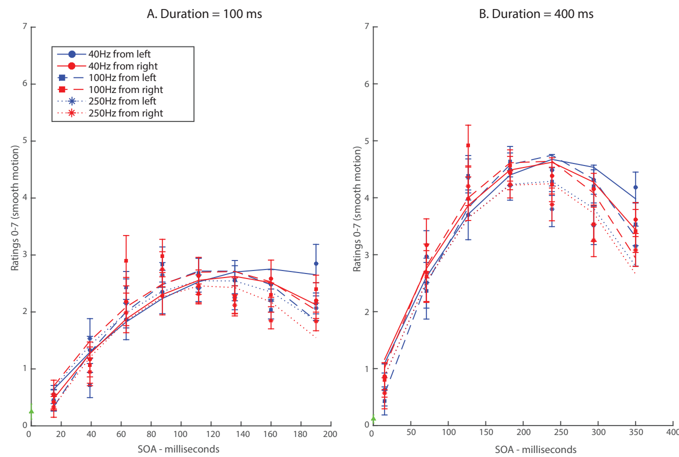

Fig. 5. Plots of the ratings of the illusion of movement (x-axis) per SOAs (y-axis). The left graph shows the plot for 100 ms duration, and the right graph shows the plot for 400 ms duration. Dots and lines represent raw data and model fitting, respectively.

TABLE I
OPTIMAL SOA VALUES (IN MS) AND QUADRATIC FIT (R^2) FOR THE DIFFERENT COMBINATIONS OF DURATION, FREQUENCY, AND DIRECTION.

Duration	Frequency	Direction	SOA peak (ms.)	R^2
100 ms	40 Hz	from left	158.57	.95
100 ms	40 Hz	from right	123.62	.83
100 ms	100 Hz	from left	123.32	.89
100 ms	100 Hz	from right	133.06	.94
100 ms	250 Hz	from left	125.33	.66
100 ms	250 Hz	from right	120.51	.86
400 ms	40 Hz	from left	247.45	.96
400 ms	40 Hz	from right	226.12	.95
400 ms	100 Hz	from left	216.27	.89
400 ms	100 Hz	from right	226.04	.96
400 ms	250 Hz	from left	213.09	.86
400 ms	250 Hz	from right	213.05	.90

Subjects represented our random variable (model 1). Our model, had a R^2 = .52, AIC[1] = 6541.12.

When inspecting Fig.5, there seems to be an interaction between the duration and SOA. Hence, we accounted for this interaction in our model. After fitting our dataset into a quadratic function, y = duration + SOA + SOA^2 + duration:SOA (model 2), the AIC decreased to 6386.93 (R^2 = .56). A likelihood ratio test between the two models suggested model 2 as more accurate in predicting our data, $p < .0001$. Therefore our final model is:

$$1)\quad y = 0.47 - 5*10^{-4}*dur + 2*10^{-2}*SOA - 9*10^{-5}*SOA^2 + 4*10^{-5}*dur : SOA$$

[1]The Akaike information criterion (AIC) is a parameter used to compare different models, whereby the smaller the value between two models, the better the model fits the data (F. Korner-Nievergelt, T. Roth, S. von Felten, J. Guelat, B. Almasi, and P. Korner-Nievergelt (2015). Chapter 11 - Model Selection and Multimodel Inference, in Bayesian Data Analysis in Ecology Using Linear Models with R, BUGS, and STAN, pp. 175-196.).

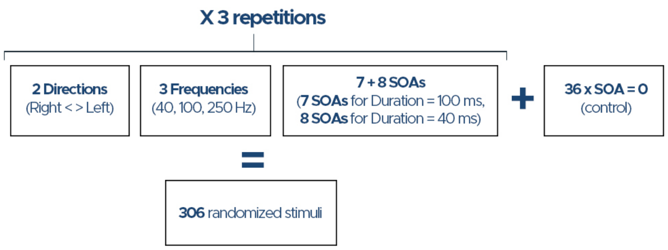

Fig. 6. Experimental design for experiment 2. Every mid-air haptics stimulus was a combination of the four variables (i.e., duration, direction, frequency, and SOA), and a control condition with SOA set at 0, for a total of 306 randomized stimuli. The picture is not representative of the order of presentation of the stimuli.

where the colon (:) represents an interaction. In this experiment we investigated the optimal parameters to achieve a smooth ATM between the two hands, employing a static point. In the next section, we will discuss the optimal parameters needed when using a dynamic point.

V. Experiment 2: Tactile Illusion of Movement with a Dynamic Focal Point

The aim of this second experiment was to investigate whether using a dynamic point instead of a static focal point on the palms would result in a smoother sensation of movement. For this experiment, we used again the same psychophysical approach used for experiment 1 (see Section IV-A).

A. Method

This second experiment consisted of 102 randomized tactile stimuli repeated three times, for a total of 306 stimuli. Participants received the same familiarization as in experiment 1 before proceeding to the study phase. An overview of the experimental design and conditions is shown in Fig. 4.

The procedure was the same as for experiment 1, with the key difference that the mid-air tactile stimulus was a dynamic focal tactile point instead of a static one. The focal point moved along a straight line from one hand to the other (see Fig. 1), being in contact with the participants' palm for a length of 4 cm, with a speed varying according to the duration of the stimulus. During the experiment, every stimulus was a combination of four variables: duration (100 ms and 400 ms), SOA (two different sets of eight and seven intervals, depending on the stimulus's duration, plus the control SOA), frequency (40 Hz, 100 Hz, and 250 Hz) and direction (from left to right and vice-versa). Stimuli were presented one at a time, with at least a five-second gap to avoid tactile habituation. Each block was separated by a two-minute break. Participants wore headphones to mask environmental and device noises, and a beep sound was played through the headphones before the beginning of each trial. Overall, the experiment lasted 50 minutes. All participants were compensated with a £7.5 voucher for participating in the experiment.

B. Participants

A total of 20 participants took part in the study (nine females, age μ = 26, SD = $\pm$ 6.36). They had normal or glasses/lens corrected vision and no history of neurological or psychological disorders. All participants were right-handed. Upon arrival, participants were asked to read the information sheet and sign a consent form before the task was explained.

C. Results

To analyze the data, we followed the same procedure as in experiment 1. Fig. 7 illustrates the average ratings as a function of SOA for the two test durations, the two directions, and the three frequencies, along with best-fit quadratic trends. The two lowest parts of the curves correspond to low SOAs (merged tactile perception) and high SOAs (discrete tactile perception). The peaks of the curves correspond to the optimal values of the SOAs and are reported in Table II.

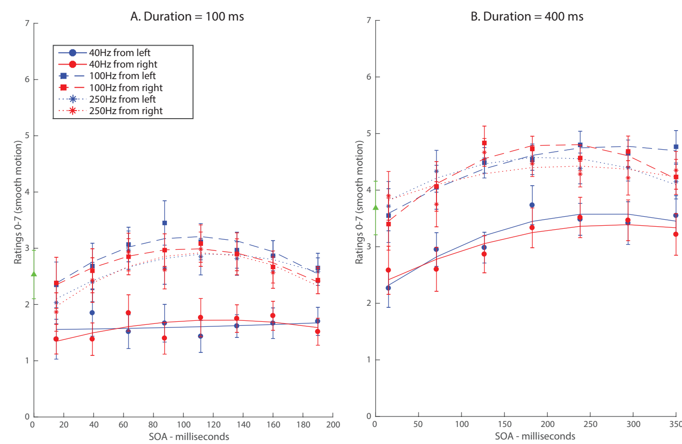

Fig. 7. Plots of the ratings of the illusion of movement (x-axis) per SOA (y-axis). The left graph shows the plot for the 100 ms duration, and the right graph shows the plot for the 400 ms duration. Dots and lines represent raw data and model fitting, respectively.

On average, the optimal SOA value was found to be 175.53. As in experiment 1, our hypothesis was that with very small and very large SOA values, participants' rating of the smoothness of the illusion of movement should decrease. Therefore, we fit a quadratic model to describe our dataset: y = duration + SOA + SOA^2 (model 1). Moreover, from Fig.7,

TABLE II
Optimal SOA values (in ms.) and quadratic fit (R^2) for the different combinations of duration, frequency, and direction.

Duration	Frequency	Direction	SOA peak (ms.)	R^2
100 ms	40 Hz	from left	58.49	.07
100 ms	40 Hz	from right	107.34	.83
100 ms	100 Hz	from left	121.75	.80
100 ms	100 Hz	from right	124.48	.40
100 ms	250 Hz	from left	104.20	.95
100 ms	250 Hz	from right	112.95	.82
400 ms	40 Hz	from left	266.78	.87
400 ms	40 Hz	from right	280.84	.96
400 ms	100 Hz	from left	200.79	.87
400 ms	100 Hz	from right	285.47	.85
400 ms	250 Hz	from left	214.88	.90
400 ms	250 Hz	from right	228.40	.45

the curve for the 40 Hz frequency seems to have obtained a lower rating compared to the other two frequency curves (i.e., the 100 and the 250 Hz). Indeed, during the study, some participants referred to not being sure of the perception of this frequency because it was "too weak" and "subtle". Therefore, in our model we treated the variable frequency as categorical and used the 40 Hz frequency as the baseline. Our model obtained a R2 = .45. Below, we report the equations for the 40 Hz, 100 Hz, and 250 Hz frequencies:

2) $y = .66 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

3) $y = 1.2 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

4) $y = 1.1 + 4 * 10^{-3} * dur + 6 * 10^{-3} * SOA - 1.2 * 10^{-5} * SOA^2$

These results are consistent with the shape of the curves shown in Figure 7 (see the intercept term), where the 100 and 250 Hz frequencies seem to overlap, with the 40 Hz frequency having the lowest rating scores. In fact, some participants mentioned uncertainty about perceiving this frequency or described it as very light and hard to perceive.

In summary, based on our two experiments, we have created a first-time insight into the use of mid-air haptics for creating a tactile illusion of movement, testing a static versus a dynamic focal point. Below, we first discuss the findings by comparing both stimulation approaches, and then we present a discussion comparing our results using mid-air touch with the use of physical touch in the creation of ATM. We conclude with a discussion on future investigations and opportunities for design.

VI. Comparing static vs. dynamic mid-air focal points

In this section, we are interested in comparing results from experiment 1 (static point) with experiment 2 (dynamic point), to understand how the perception of ATM is affected by the two different approaches employed in this study.

Upon a preliminary inspection, the rating curves of experiment 1 and experiment 2 (see Fig. 5 and 7) appear different, with the curves of experiment 1 being sharper and having a clear peak for the optimal SOAs. Moreover, when the SOAs are too short or too long, participants' ratings clearly decrease. On the contrary, for experiment 2, it is harder to visualize the same trend.

We hypothesize that when a dynamic focal point is delivered to the hands (experiment 2), subjects will always perceive a certain amount of movement, that is, the perceptual information will be perceived as more confusing compared to a static focal point (experiment 1). In other words, in the dynamic focal point condition, the SOA seems to play a minor role in the delivery of the illusion of movement. This means that when we want to render a smooth sensation of movement using a dynamic focal point, the SOA is not as crucial as for a static focal point.

Next, to compare the results obtained from experiment 1 with those of experiment 2, we estimated the linear and quadratic terms for predicting smoothness ratings from SOA at each duration (100 ms and 400 ms) and frequency (40 Hz, 100 Hz, and 250 Hz) for each subject (20). Therefore, we extracted six linear and six quadratic terms for each subject. We checked the distribution of these data through a Shapiro-Wilk test. Then, we ran separate independent t-tests between the linear and quadratic terms of data from experiment 1 and 2 across duration and frequency. If the distribution of a certain set of data did not follow a normal distribution, we employed a Mann-Whitney U test for the comparison.

When compared across the two experiments (static vs. moving mid-air point), the linear and quadratic terms obtained from the quadratic fitting of the smoothness ratings led to statistical differences in all cases (all the p-values $< .001$). The linear and quadratic coefficient of data from experiment 2 were lower in all cases compared to those of experiment 1. This demonstrates that the curves from Fig. 7 (experiment 2) are indeed flatter than those from Fig. 5 (experiment 1). This confirms that when we deliver a moving point to the hands, the SOA does not play a fundamental role, and participants tend to rate the smoothness of motion always in the same way. This could confirm that the physical and illusory movement provided on the hands are conflated in participants' perception.

Further, we were interested in understanding if the smoothness of motion ratings for experiment 2 were than those of experiment 1. We calculated the peaks of the curves for the smoothness of motion ratings for each participant (N = 20), for each duration (100 ms and 400 ms), and at each frequency (40 Hz, 100 Hz, and 250 Hz). Similarly to the previous analyses, we used an independent t-test or a Mann-Whitney U test, depending on the shape of the data distribution. For the duration = 100 ms we did not obtain any significant results (p. $> .05$). On the contrary, for the duration = 400 ms, we found two statistical differences: between the 40 Hz frequencies (p. = .01, 40 Hz-exp1-mean = 4.8; 40 Hz-exp2-mean = 3.8) and between the 250 Hz frequencies (p. = .05, 250 Hz-exp1-mean = 4.4; 250 Hz-exp2-mean = 5.1).

In light of these results, we cannot say if experiment 2 achieved a higher illusion of movement. Indeed, as previously stated, the 40 Hz frequency in experiment 2 was not well perceived, hence the significant difference. Participants reported the 40 Hz frequency as too low, too subtle, or too sparse. It might be that the skin sensitivity along the stimulated location was not uniform, and an already subtle frequency would result in a confused perception. For the 250 Hz, the p. value is borderline, and it does not allow for strong conclusions. As this is the first investigation of mid-air tactile stimuli for creating ATM, further studies are needed to validate our research.

VII. Discussion

This study investigated, for the first time, the occurrence of ATM using mid-air haptic technology, comparing a static versus a dynamic tactile focal point. With experiment 1 we established that it is possible to elicit an illusion of movement between two unconnected hands by using a static focal point. We then determined and described the optimal parameters to achieve a smooth tactile illusion of movement using a psychophysical approach. We generated a perceptual model that expresses the relation between the duration and SOA of the tactile stimuli (model 1). This model specifies the optimal parameters to use for achieving a smooth illusion of motion between the hands. The most relevant variables impacting users' perception are the duration and the SOA of the tactile stimuli, confirming previous results ([3], [4], [36]). In experiment 2, we replicated experiment 1 using a dynamic focal point. We derived a perceptual model (model 2,3,4) for the optimal parameters to achieve a smooth illusion of movement.

To enrich our understanding of creating a tactile illusion of movement, we compared results from experiment 1 and experiment 2 with respect to their effectiveness in achieving a smooth sensation of movement. The results suggest that there is no difference in the perceived smoothness of motion, but using a moving point could inflate the rating of the illusory motion.

VIII. Limitations and Future Research

Our results indicate that mid-air touch represents a promising approach to deliver an illusion of motion. In this section, we discuss some limitations and challenges of employing mid-air tactile technology, and we provide ideas for future research.

The mid-air haptic device provides a subtle tactile feedback (like puffs of air, or a breeze [35]), and as shown in experiment 2, low frequencies might constitute a limitation. Previous research has shown that the waveform of a tactile stimulus can lower or increase the absolute tactile thresholds (e.g., sinusoidal vs. square) [37]. Future work could investigate ATM produced by delivering the tactile mid-air stimulus through a different waveform (e.g., square shape) to observe whether the effect of the illusion would be strengthened.

In this study, we investigated ATM using a device positioned statically on a desk to set the basis for understanding the phenomenon as mediated by mid-air touch. Future work could explore how this illusion of movement would change when the participant is free to move their hands in space.

Our findings and prior work [3], [4] have shown the occurrence of ATM between the hands. It would be interesting to test, with both mid-air and physical touch, the possibility of recreating an effect of movement between different parts of the body, for example, hands and feet, and to observe if the relationship between the durations and SOA of the tactile stimuli would change. Finally, other technologies could be used to explore ATM perception, such as wearable devices.

IX. Conclusion

This study investigated, for the first time, the occurrence of ATM using a mid-air haptic device. We obtained the optimal parameters to achieve a smooth motion using a static versus a dynamic mid-air focal point. We provided a perceptual model for each approach used. We then compared the results obtained from a static versus a dynamic point on the palms. These data suggest no difference between the two approaches, but the first (static point) might be preferable to achieve a clean sensation of motion.

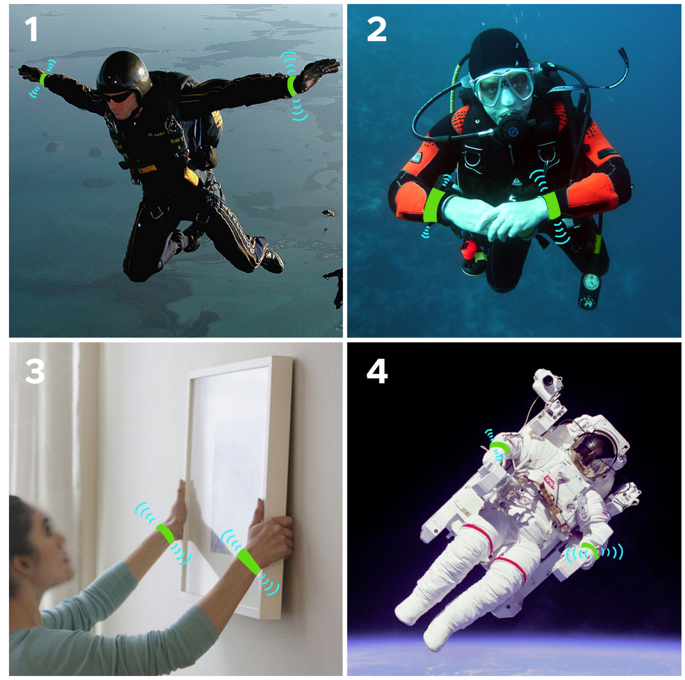

Fig. 8. Example of applications where vision could be unreliable and ATM could provide alternative orientation information. 1) Skydiving: the environment could appear visually flat. 2) Underwater: humans can lose orientation underwater. 3)ATM could be used to provide information on balance (e.g., when hanging a picture on the wall, when the picture is straight, the motion will not be perceived anymore). 4) In space, humans can lose orientation.

Knowing the optimal parameters required to model a smooth sensation of movement can allow for new experiences in VR and non-VR environments. We can now feel the movement of the wind and the waves of the sea. In addition, the phenomenon of ATM could be used to provide directional information (e.g., as a tactile GPS) in cases where visual cues may be unreliable (e.g., in space, underwater, or when skydiving) or absent (e.g., in the dark or in the case of the visually impaired population). When in space, underwater, or free falling in the sky, our vision may be unreliable and tactile motion could help to guide us towards our target. Furthermore, this sense of motion could provide hands-free information about the current position and balance of an object we are hanging or carrying (e.g., acting as a tactile bubble level) (Fig. 8).

We believe that this study provides a valuable insight into users' perception of mid-air tactile stimulation, and it will open a space for new immersive and realistic scenarios in gaming experiences in VR, AR, and traditional games.

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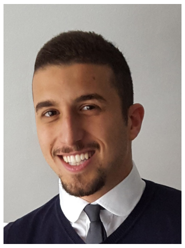

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